DARK MATTER AND GRAVITATIONAL WAVE SCIENCE

BEYOND THE STANDARD MODEL WITH GRAVITATIONAL WAVE OBSERVATIONS

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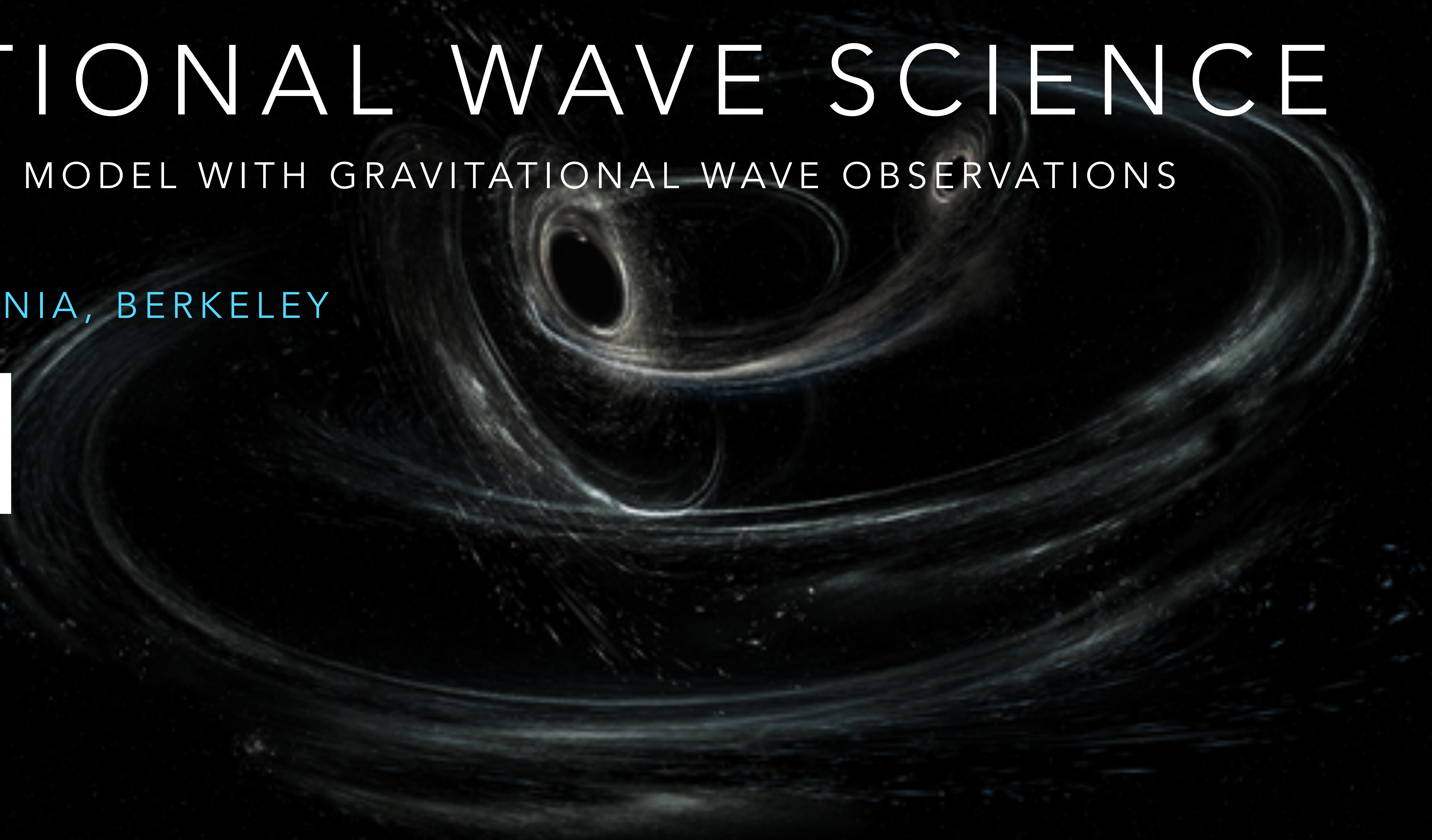

Image Credit: LIGO/Caltech/MIT/Sonoma State (Aurore Simonnet)

PAX-X AND CE SYMPOSIUM, UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN 2025

Bertone et al. (2019)

This is a rich and exciting field of research with great avenues for multi-messenger detection of dark matter candidates!

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Compact binary Coalescences and Dark matter

DETECTING GRAVITATIONAL WAVES FROM CBC(S)

- Real-time searches look for BBH, BNS, and NSBH signals with multiple search pipelines.
- >200* public alerts from significant detections to date in the fourth observing run of LIGO-Virgo-Kagra.
- Total detections so far: >290

First BBH (O1): GW150914 PBHs? *Sasaki et al. (2016)*

First BNS (O2): GW170817

First NSBHs (O3): GW200105, GW200115

NSBH in O4: GW230529 (Mass Gap BH)

From: https://emfollow.docs.ligo.org/userguide/capabilities.html

Gravitational Wave DB: https://gracedb.ligo.org/superevents/public/O4/

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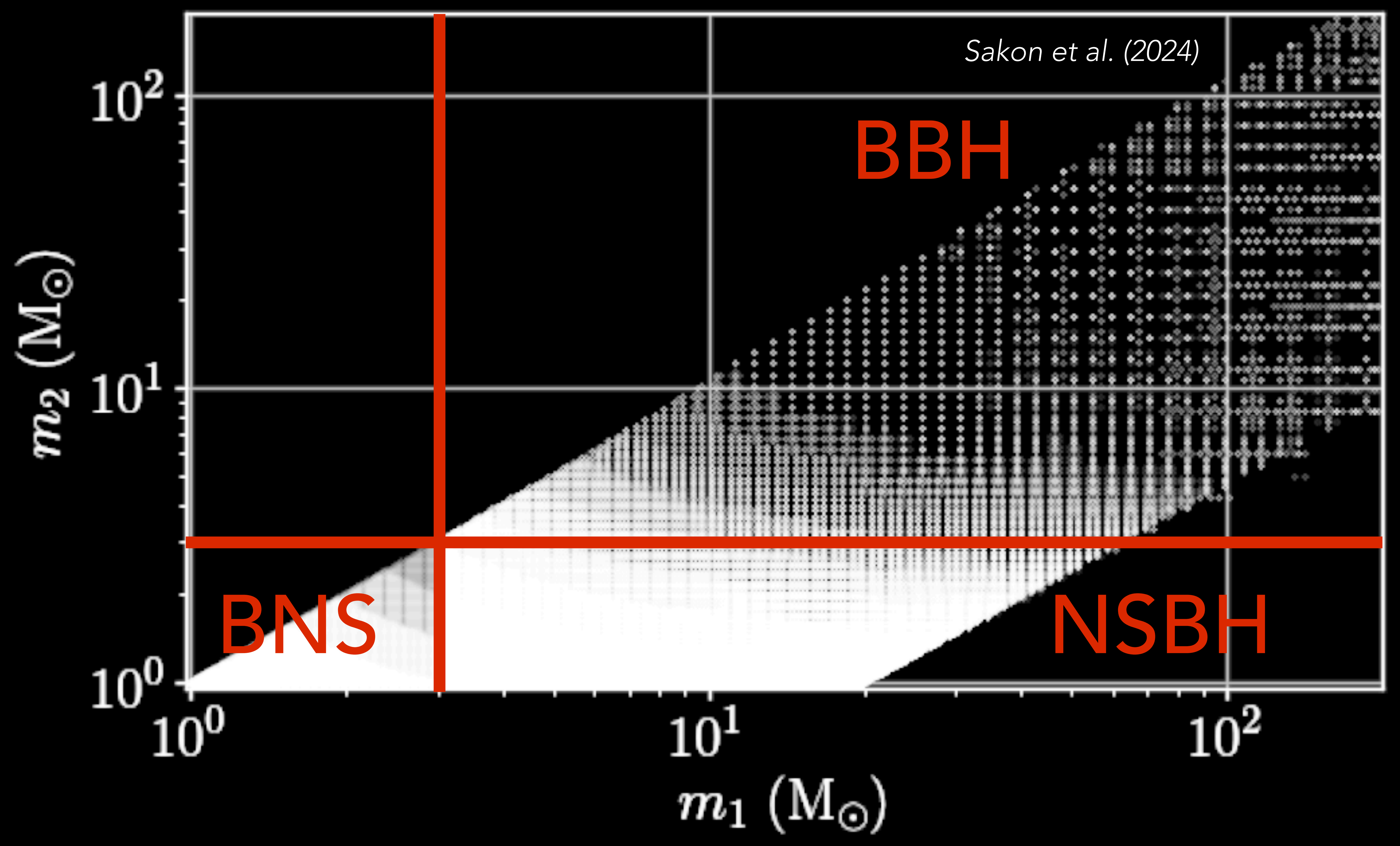
Mass of Compact objects from stellar evolution > 1.4 $M_{\odot}$



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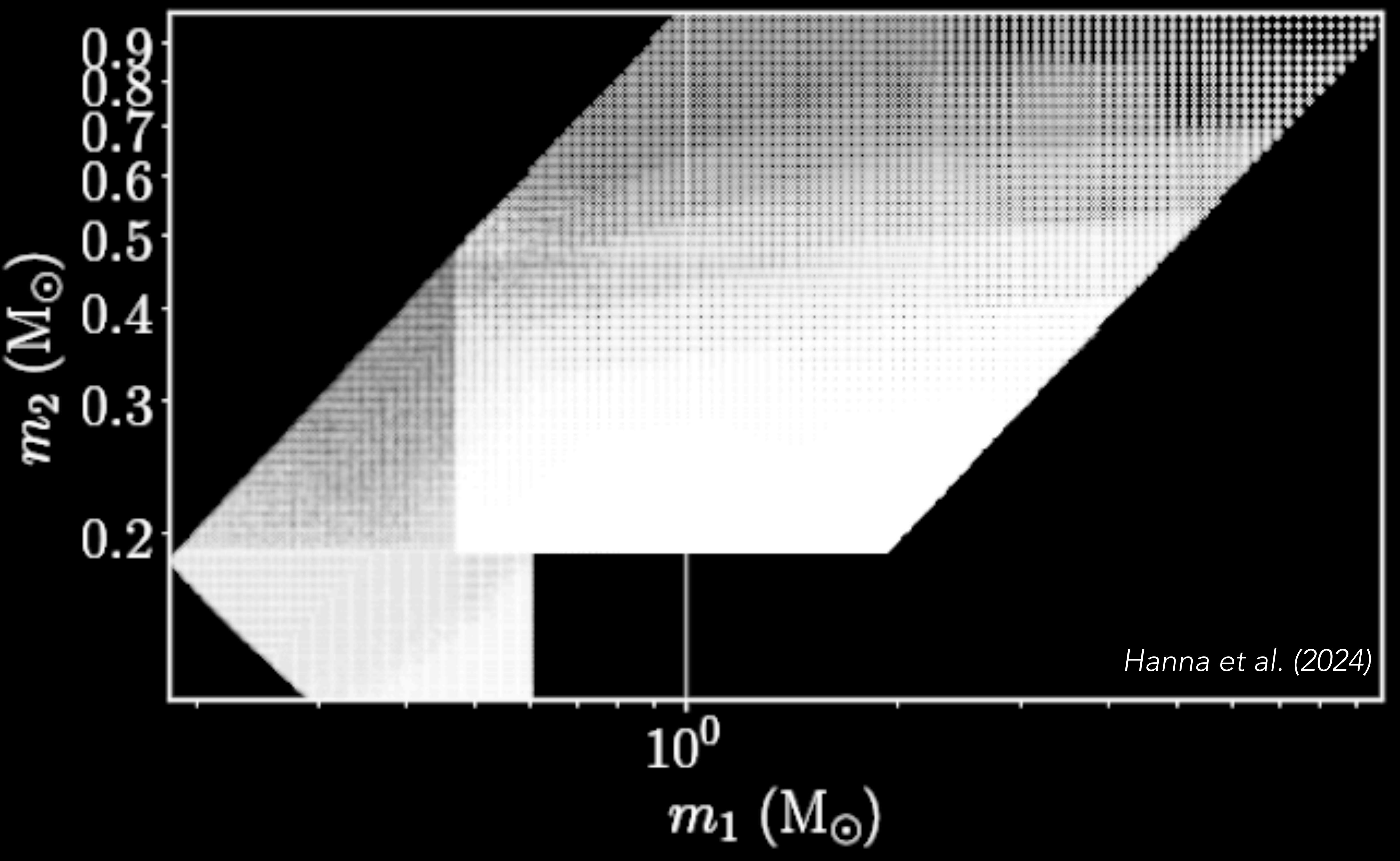
FORMATION CHANNELS BEYOND STELLAR EVOLUTION

- Primordial Black Holes
- Dissipative dark matter — Dark Black Holes
- Neutron Star implosion from dark matter accumulation

SUB-SOLAR MASS SEARCHES IN GRAVITATIONAL WAVE DATA



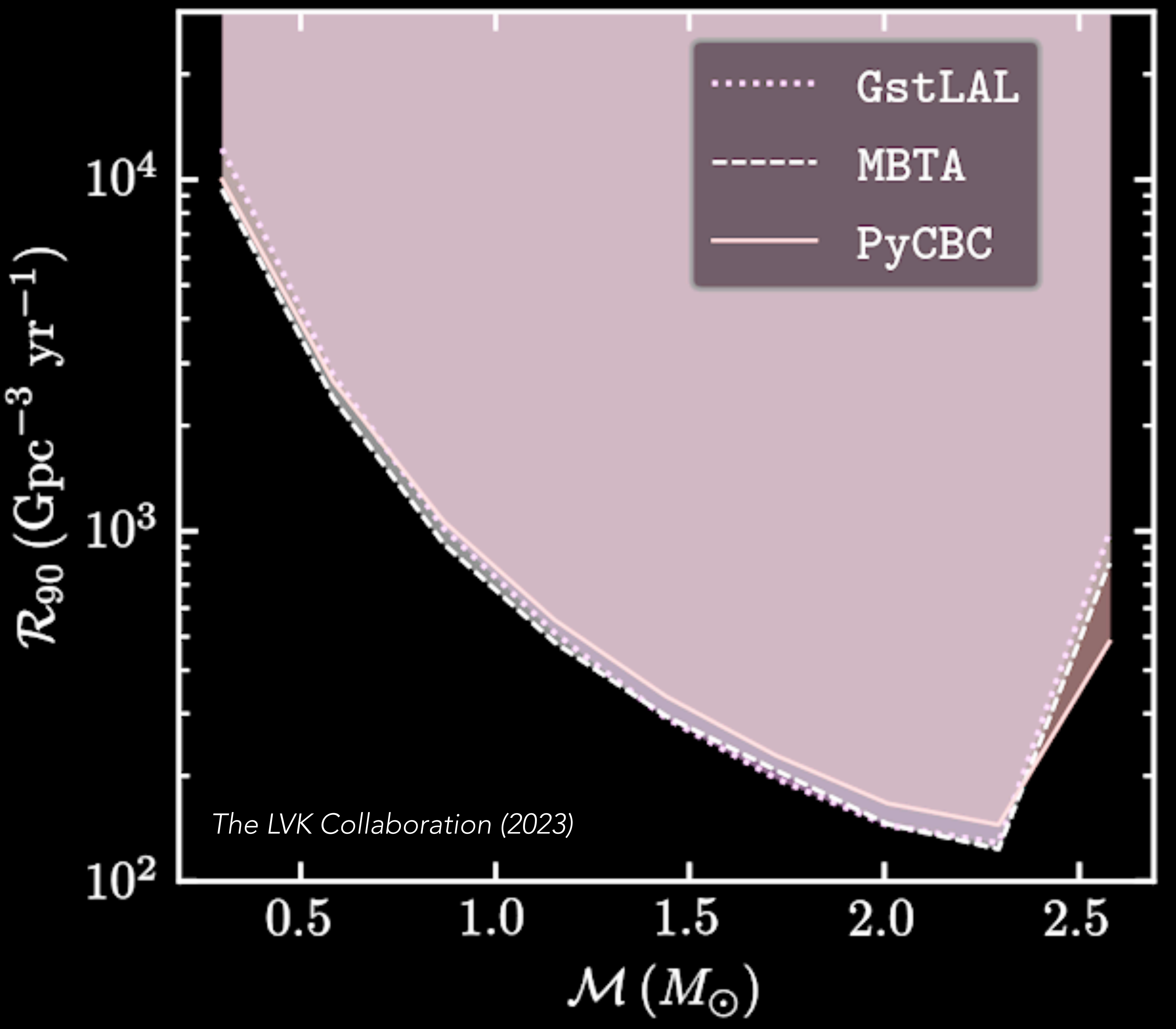
SUB-SOLAR MASS SEARCHES IN DATA FROM LIGO-VIRGO

- Searches performed by multiple independent search pipelines.

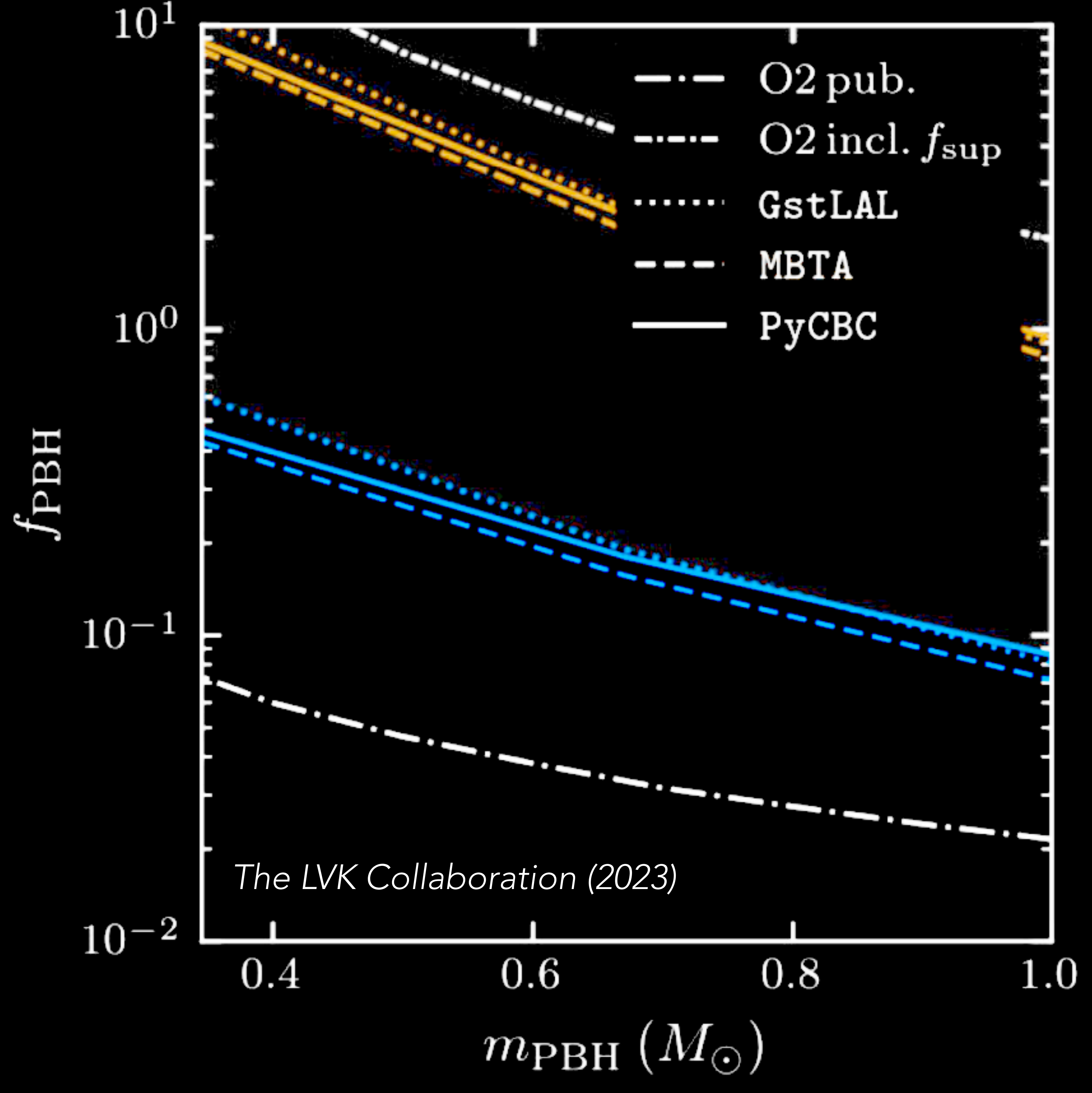
  Nitz et al. (2022), The LVK Collaboration (2023)

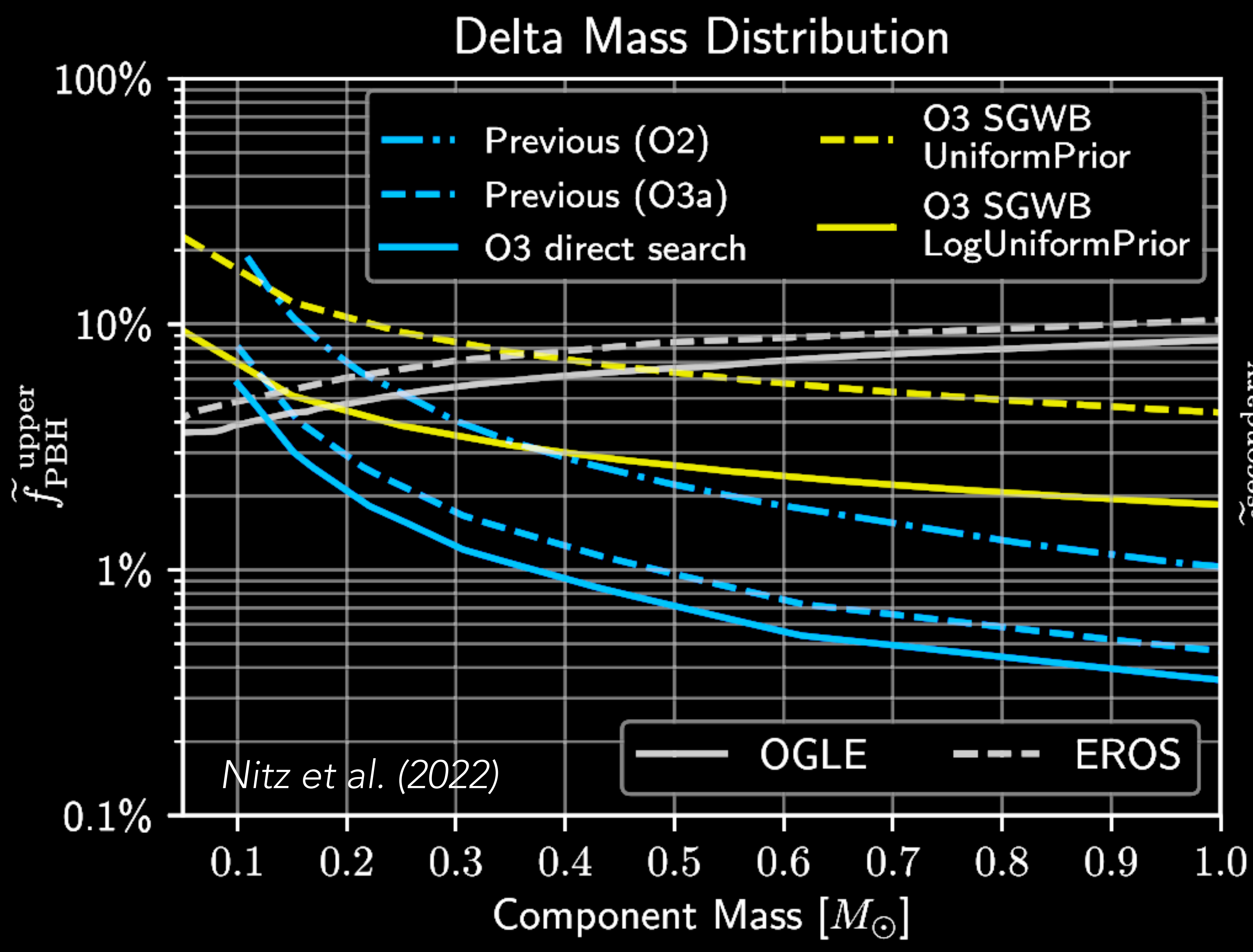
- No detections reported from searches in data from O1, O2 and O3.

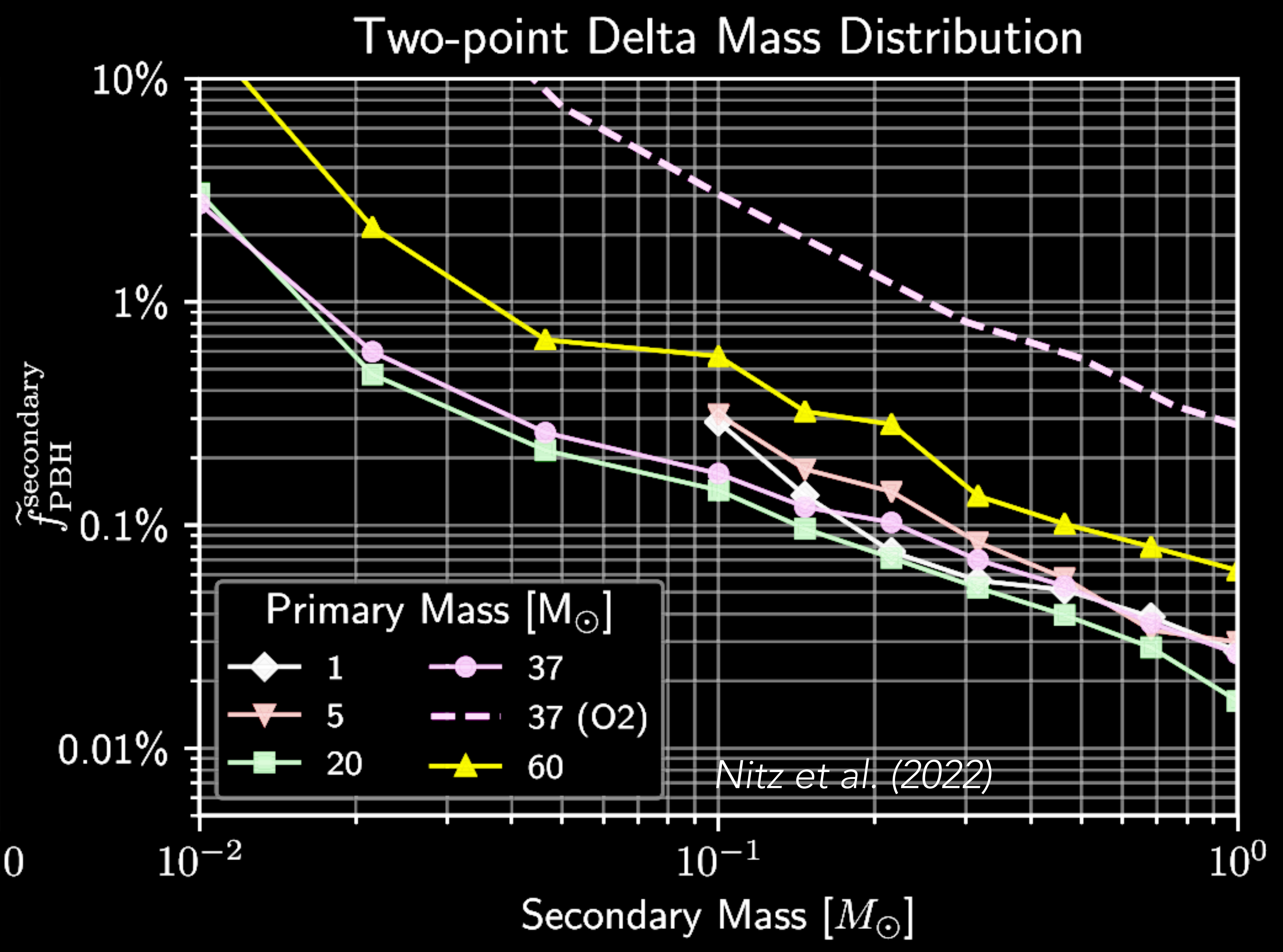
- Upper limits on Merger Rates - *100 per Gpc^3 yr^-1 at chirp mass of 2 M_sun.*



PRIMORDIAL BLACK HOLES







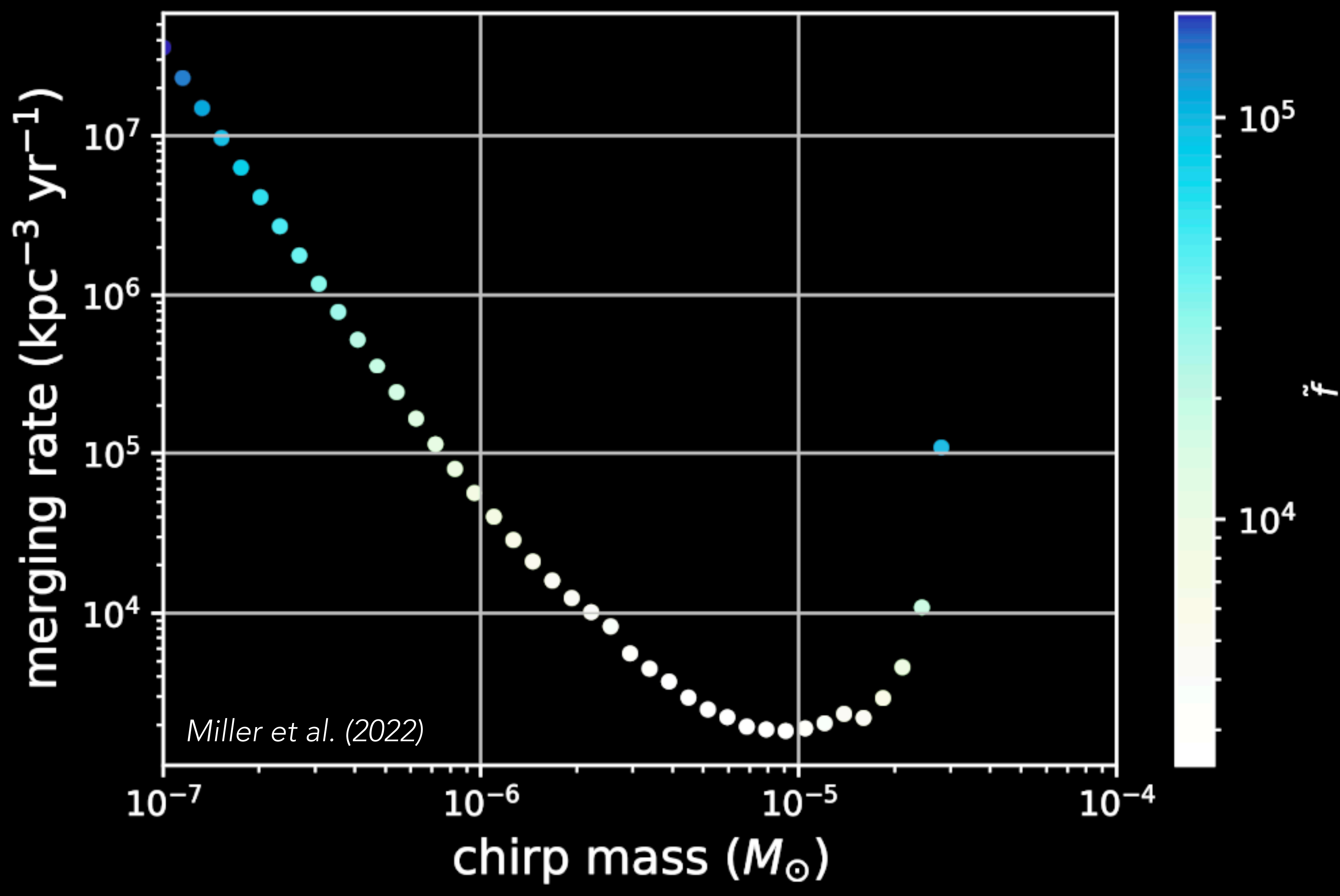
Constraints on the abundance of sub-solar mass PBHs
From astrophysical rate limits.

PRIMORDIAL BLACK HOLES

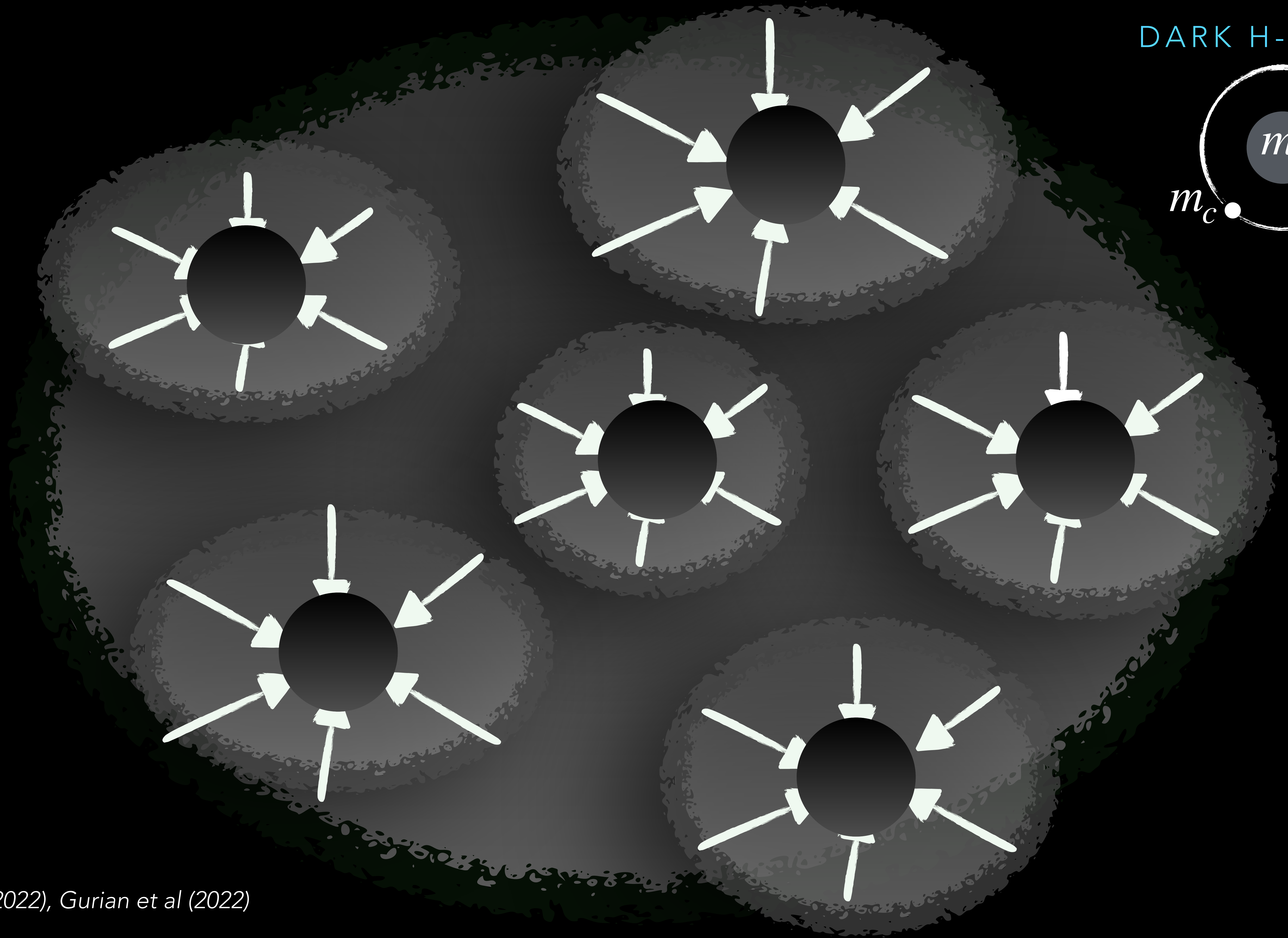
BEYOND SUB-SOLAR MASS SEARCHES IN GW STRAIN DATA

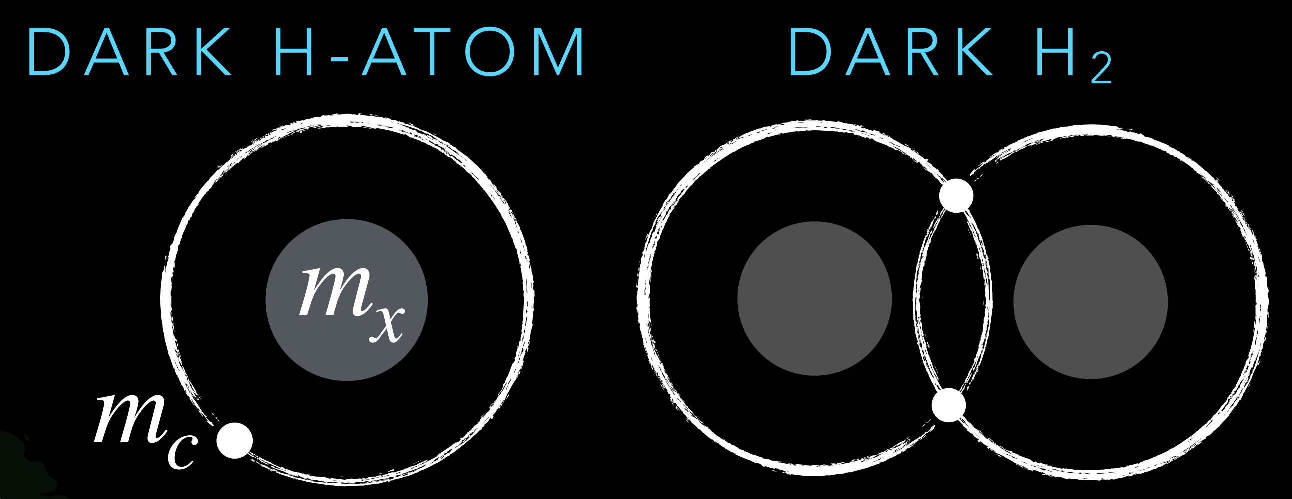
Quasi-monochromatic GW signals from **planetary-mass and asteroid-mass** PBH binaries.

Use limits from continuous wave searches to constrain the merger rate and the abundance of PBH binaries.



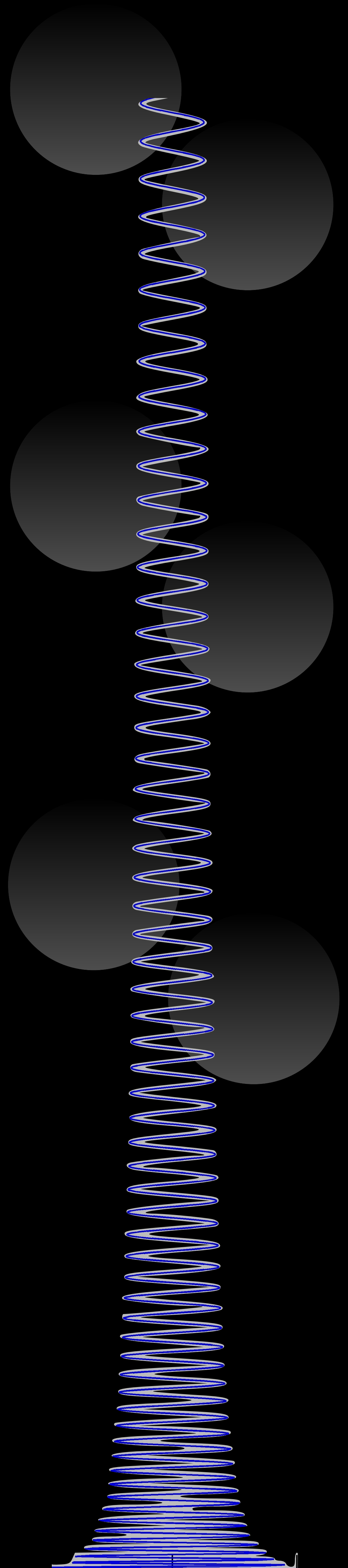
DISSIPATIVE DARK MATTER





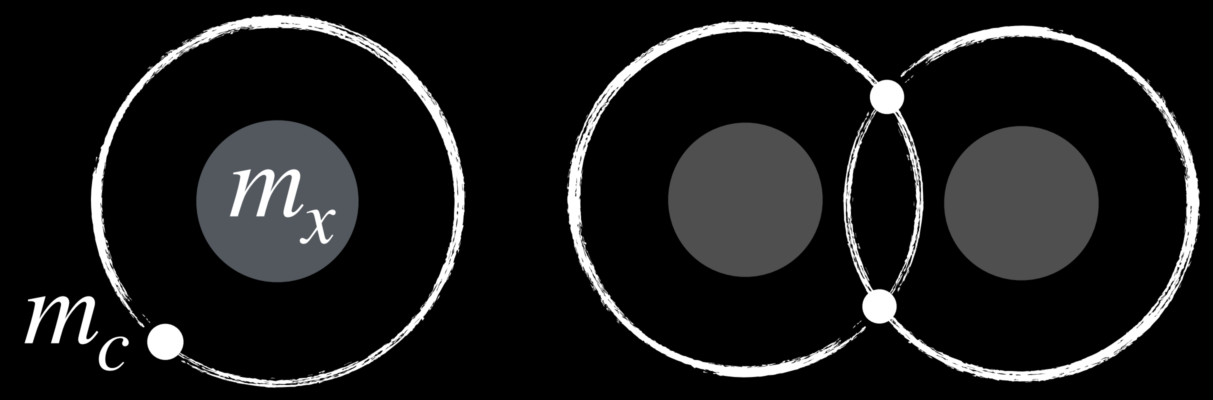
Shandera et al. (2018), Ryan et al (2022), Gurian et al (2022)

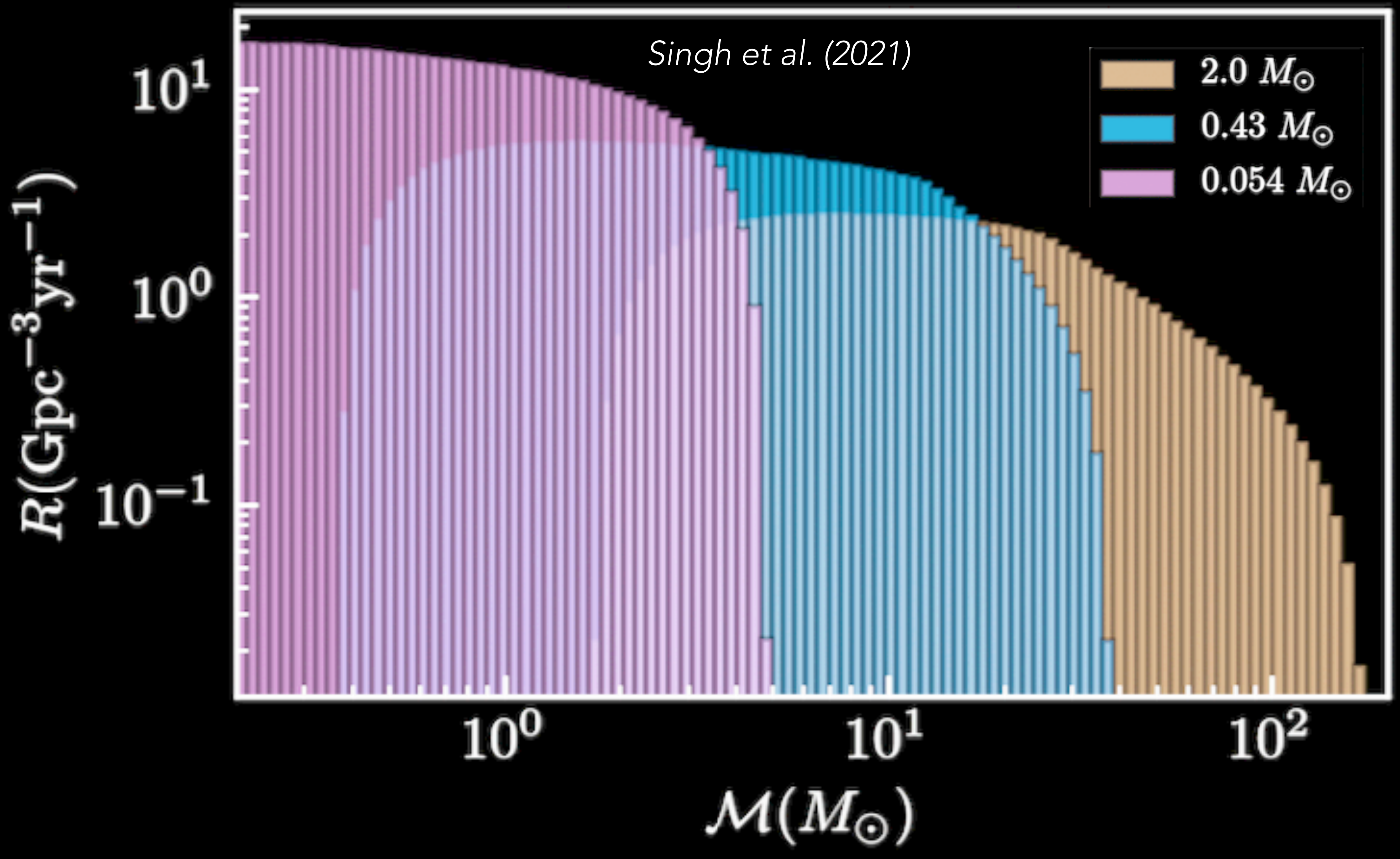
DISSIPATIVE DARK MATTER



Possibly the minimum mass of dark BHs

$$M^{\text{Dark}}_{\text{Chandrashekhar}} = 1.4 M_\odot \left(\frac{m_p}{m_x}\right)^2$$





Shandera et al. (2018)

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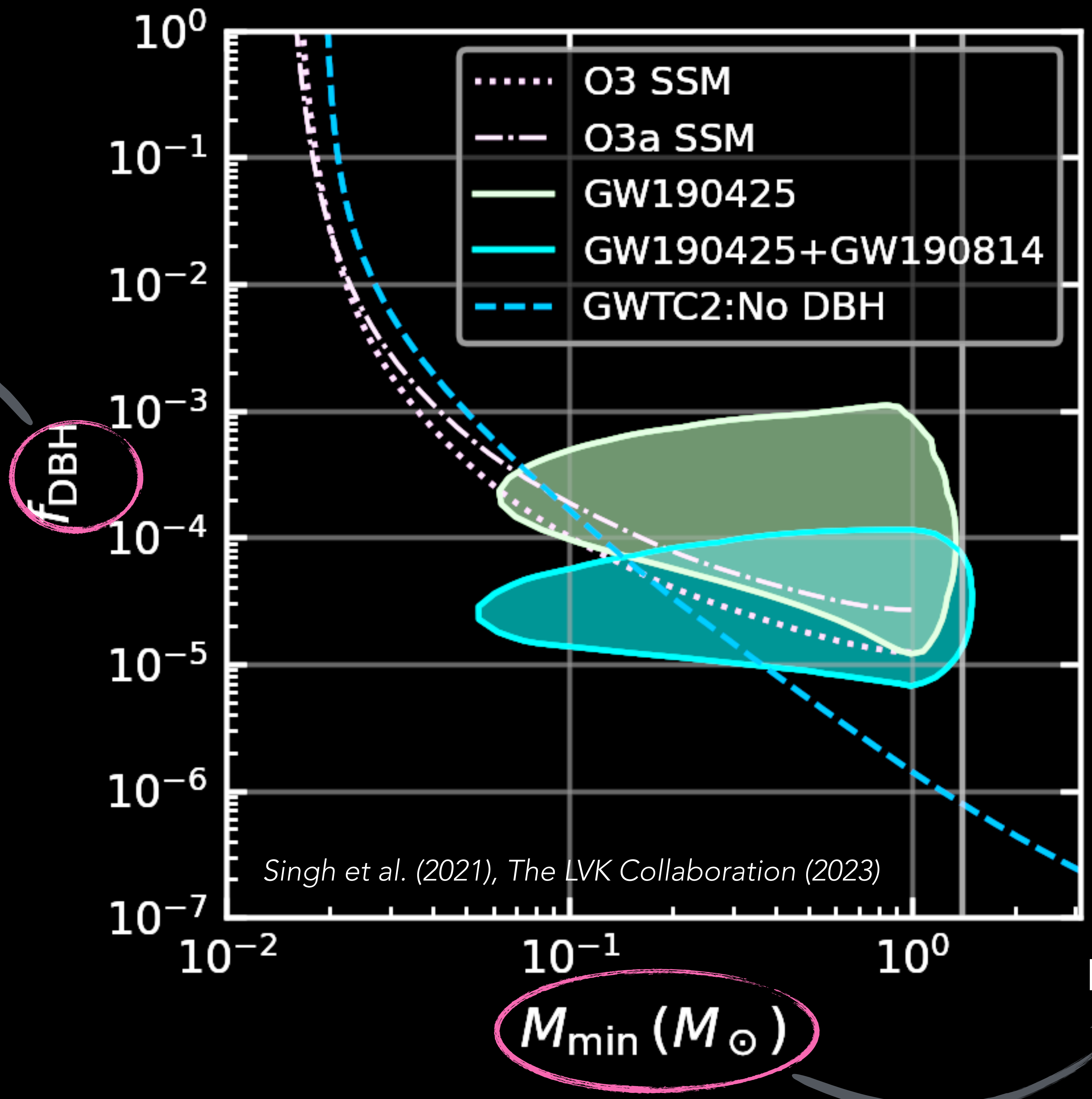
m_X [GeV]	m_c [keV]	$M^{\rm dark}_{\rm Chand.}$ $[10^{-5} M_\odot]$	$M_{\rm DBH}$ $[M_\odot]$	Rates per year: raw ($\rm MWEG^{-1}$)	aLIGO (current)	aLIGO (full)	Einstein T.	$m_1 < 1.4$ [%]	$m_1, m_2 < 1.4$ [%]
62	31	33	0.0068 – 0.68	$2.0\times10^{-6}(10^{-4})$	0.0012 (0.12)	0.020 (2.0)	60 (6000)	100%	100%
48	47	56	0.016 – 1.6	$1.3\times10^{-6}(10^{-4})$	0.0065 (0.65)	0.11 (11)	330 (33k)	99%	79%
32	70	125	0.054 – 5.4	$6.6\times10^{-7}(10^{-5})$	0.068 (6.8)	1.1 (110)	3500 (350k)	53%	9.3%
16	140	500	0.43 – 43	$1.9\times10^{-7}(10^{-5})$	0.89 (89)	22 (2200)	92k (9200k)	9.8%	0.14%

TABLE I. DBH masses and binary merger rates today, estimated using the procedure in the text, for several choices of dark proton mass m_X and dark electron mass m_c. All black hole masses are given in solar masses. In all cases we have set the dark fine structure constant to $\alpha_D = 0.01$ and the ratio of present day temperature of the dark sector to photon temperature to $\xi = 0.02$. The conservative (optimistic) rates use $f_{\rm cool} \times f_{\rm form.\,eff.} = 10^{-5}(10^{-3})$. The optimistic rate for $m_X = 16$ GeV is high enough it may already be constrained by existing LIGO data. The last two columns show the percent of binaries where one or both black holes in the binary has a mass less than the standard Chandrasekhar mass (1.4 $M_\odot$).

Appreciable merger rates albeit
dependent on dark matter particle masses

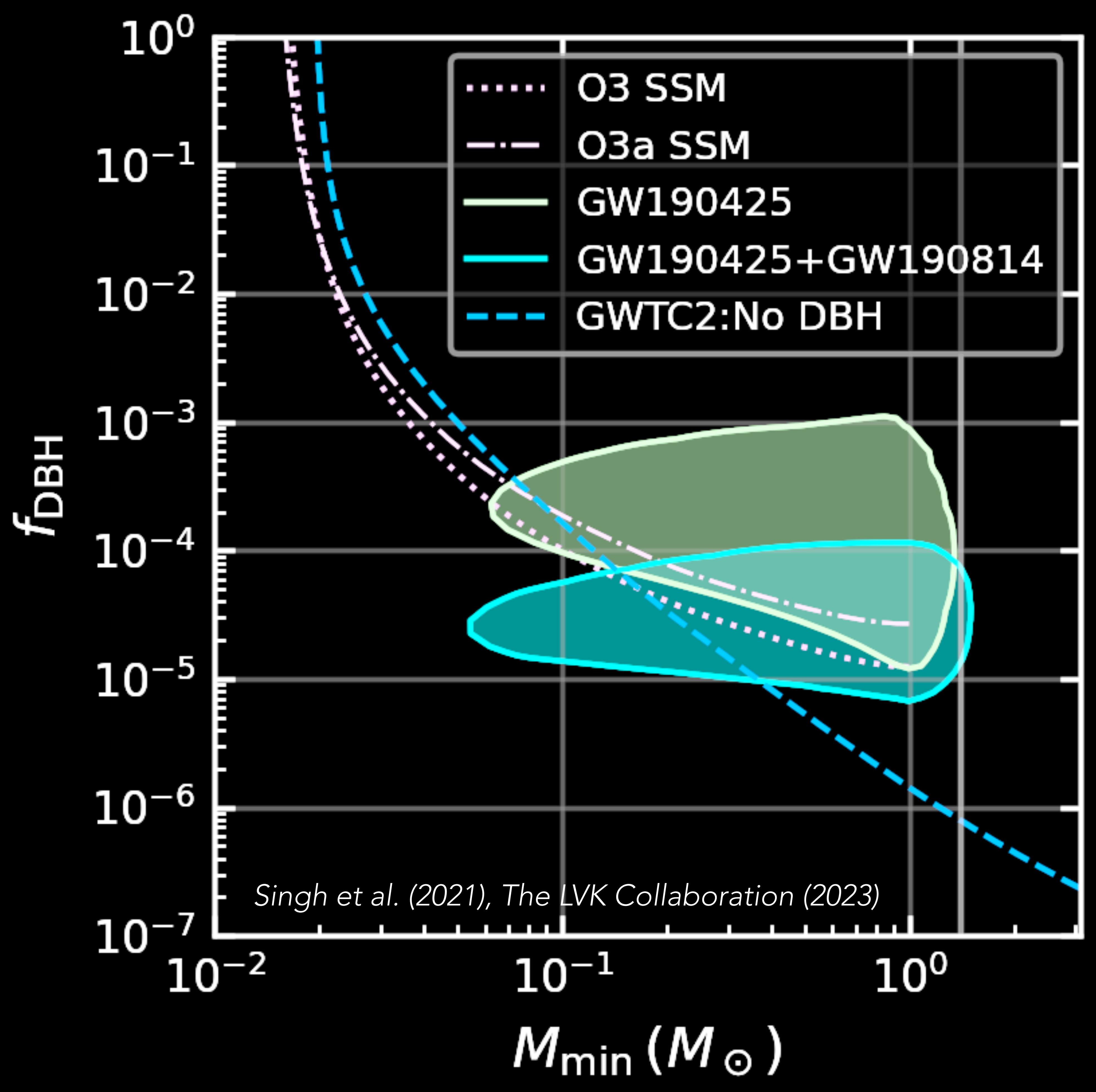
DISSIPATIVE DARK MATTER

Abundance of dark black holes - Fraction of DM in dark black holes



Minimum possible mass dark black holes

DISSIPATIVE DARK MATTER



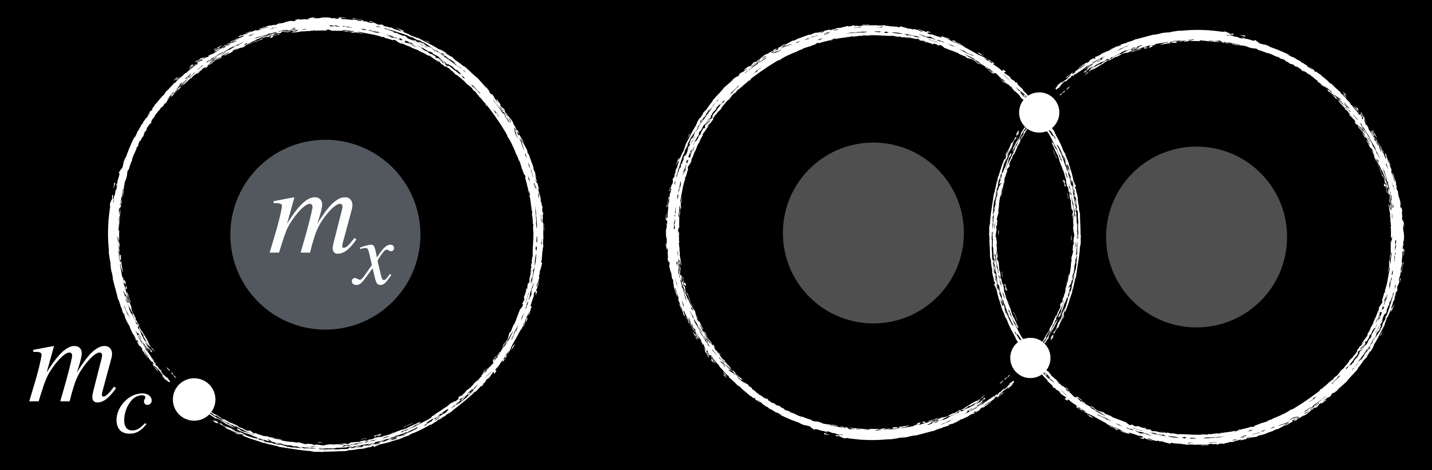


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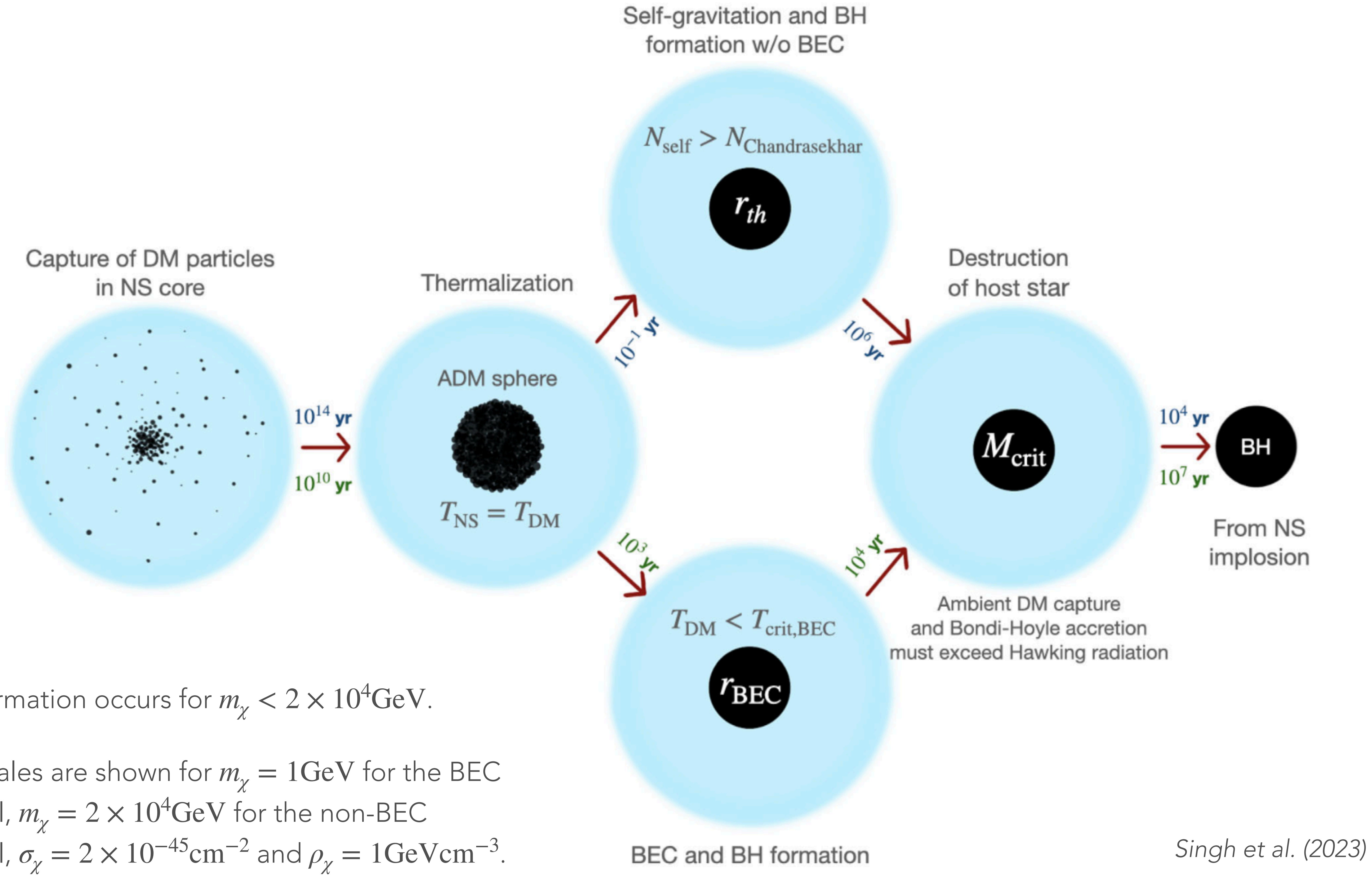
TABLE I. Probable minimum masses of dark black holes, M_{min}, and the corresponding heavy fermion masses, m_x, for the two cases of observed dark black-hole binaries. Heavy fermion masses are computed using the dark matter Chandrasekhar mass limit, by setting $M_{\text{DC}} = M_{\text{min}}$ determined from the data.

Observed DBH binary	$\mathcal{M}/M_\odot$	$M_{\text{min}}/M_\odot$	m_x/ GeV
GW190425	1.44	0.062–1.34	0.95–4.44
GW190425, GW190814	1.44, 6.1	0.054–1.50	0.91–4.76

ASYMMETRIC DARK MATTER

BLACK HOLES FROM NEUTRON STAR IMPLOSION

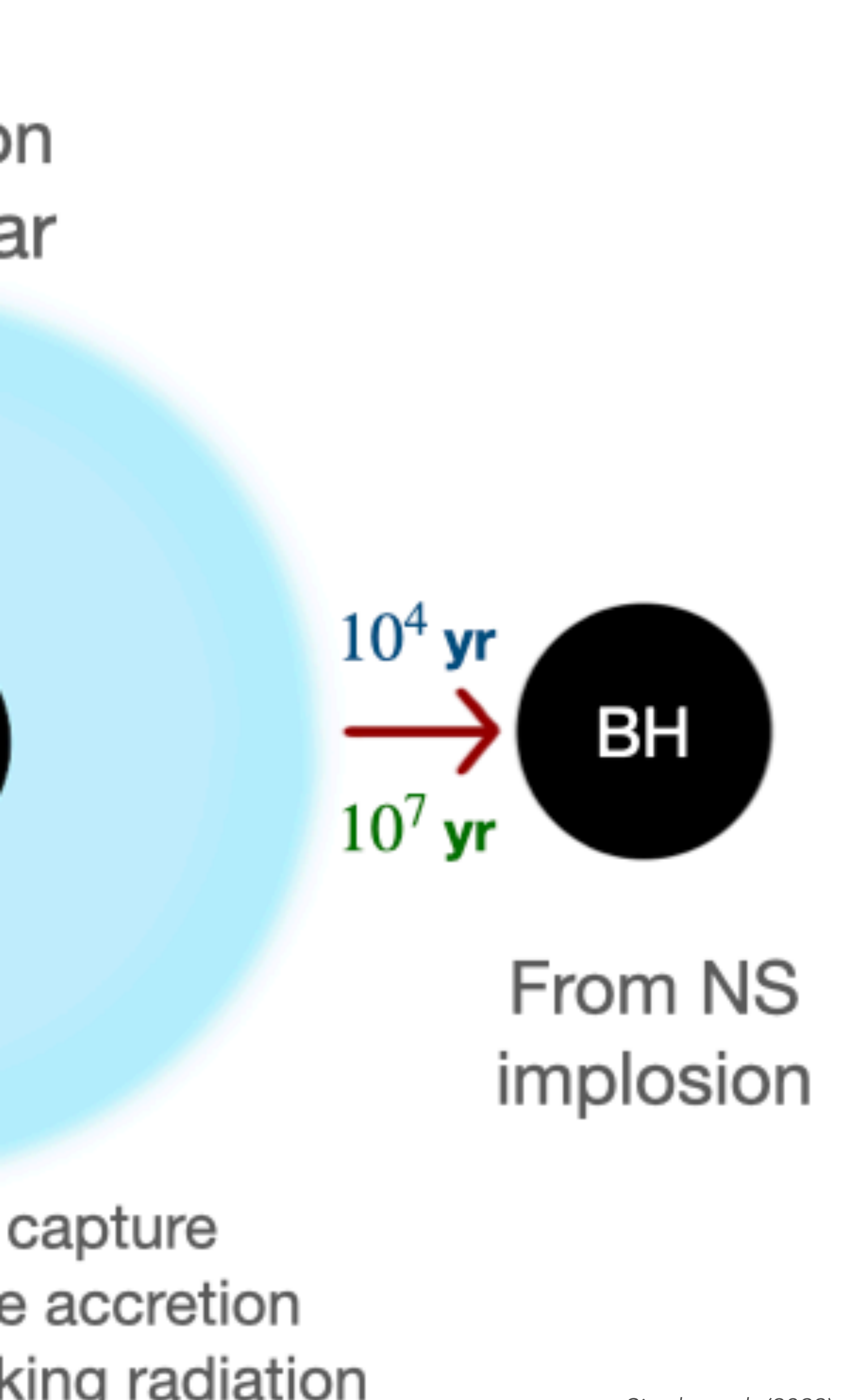


Singh et al. (2023)

BEC formation occurs for $m_\chi < 2 \times 10^4 \mathrm{GeV}$.

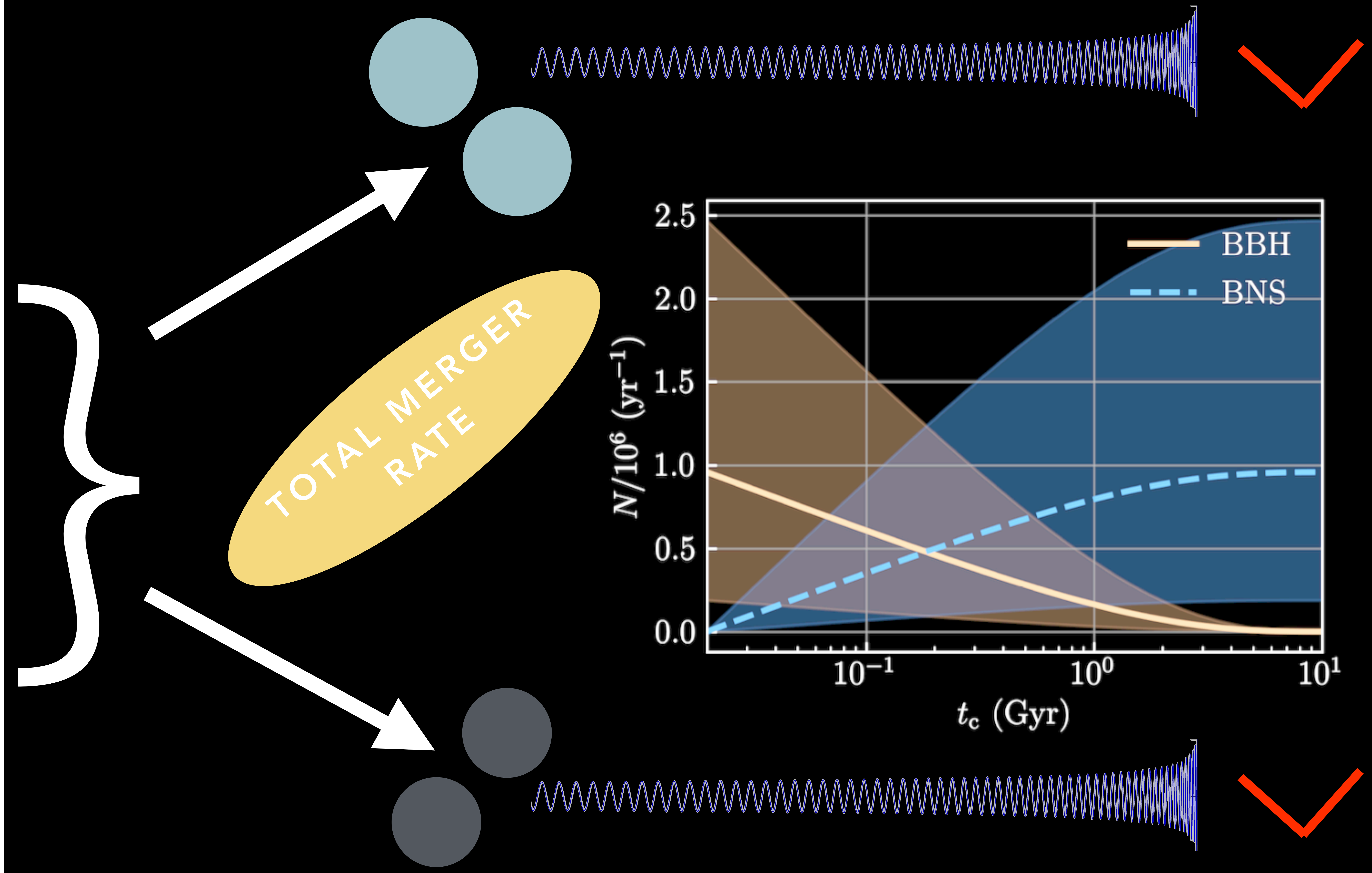
Timescales are shown for $m_\chi = 1 \mathrm{GeV}$ for the BEC channel, $m_\chi = 2 \times 10^4 \mathrm{GeV}$ for the non-BEC channel, $\sigma_\chi = 2 \times 10^{-45} \mathrm{cm}^{-2}$ and $\rho_\chi = 1 \mathrm{GeV cm}^{-3}$.

Black holes with neutron star like masses: 1-3 $M_\odot$



Singh et al. (2023)

Time to collapse > Merger time



Time to collapse < Merger time

ASYMMETRIC DARK MATTER

BLACK HOLES FROM NEUTRON STAR IMPLOSION

Star formation rate

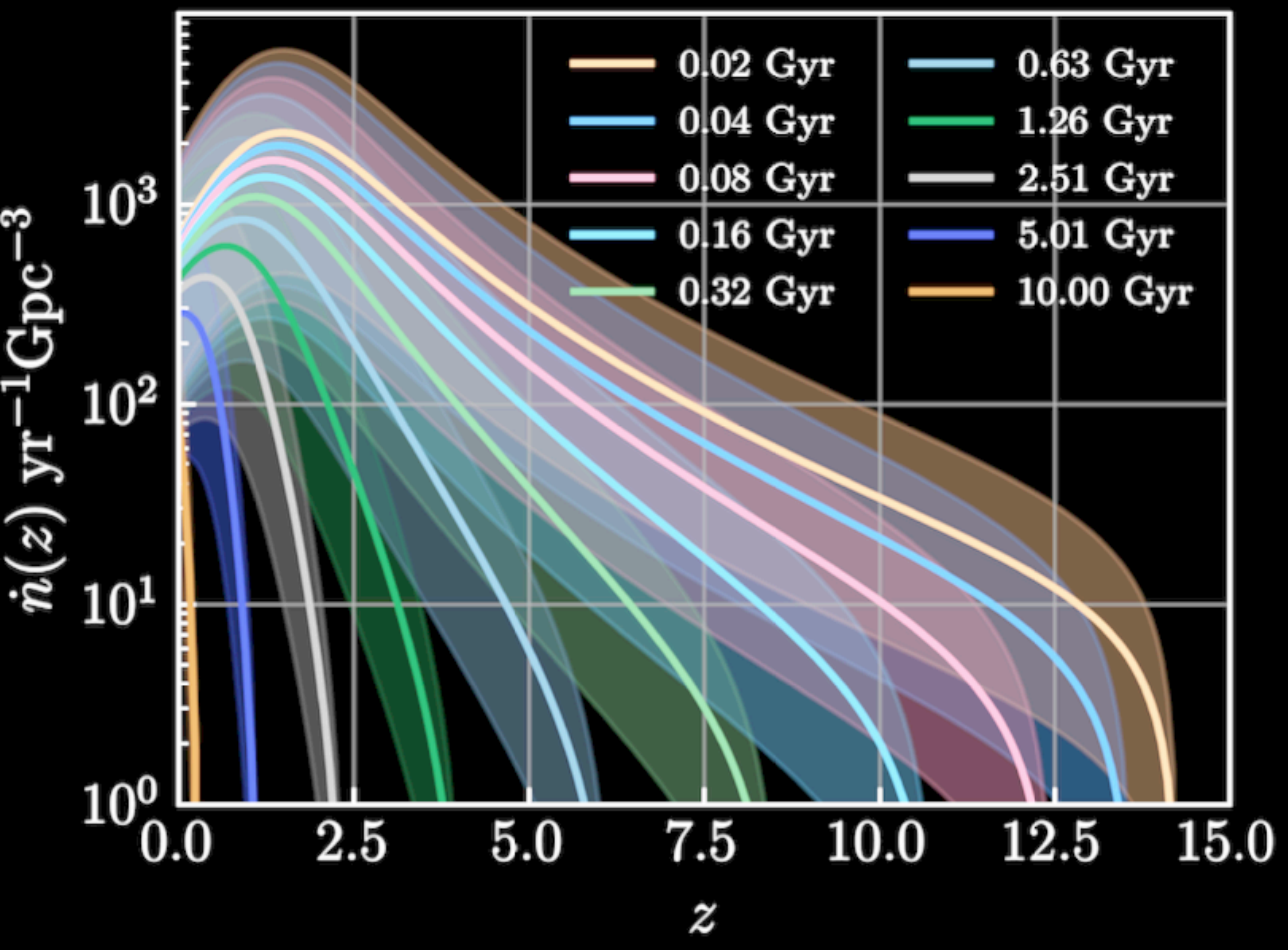
$$\dot{n}(z) = A \int_{t_d^{\min}}^{t_d^{\max}} \psi(z_f(z, t_d))\,\mathscr{P}(t_d)\,dt_d$$

Delay time distribution

$$\dot{n}(z) = \dot{n}(z)_{\mathrm{BNS}} + \dot{n}(z)_{\mathrm{BBH}}$$

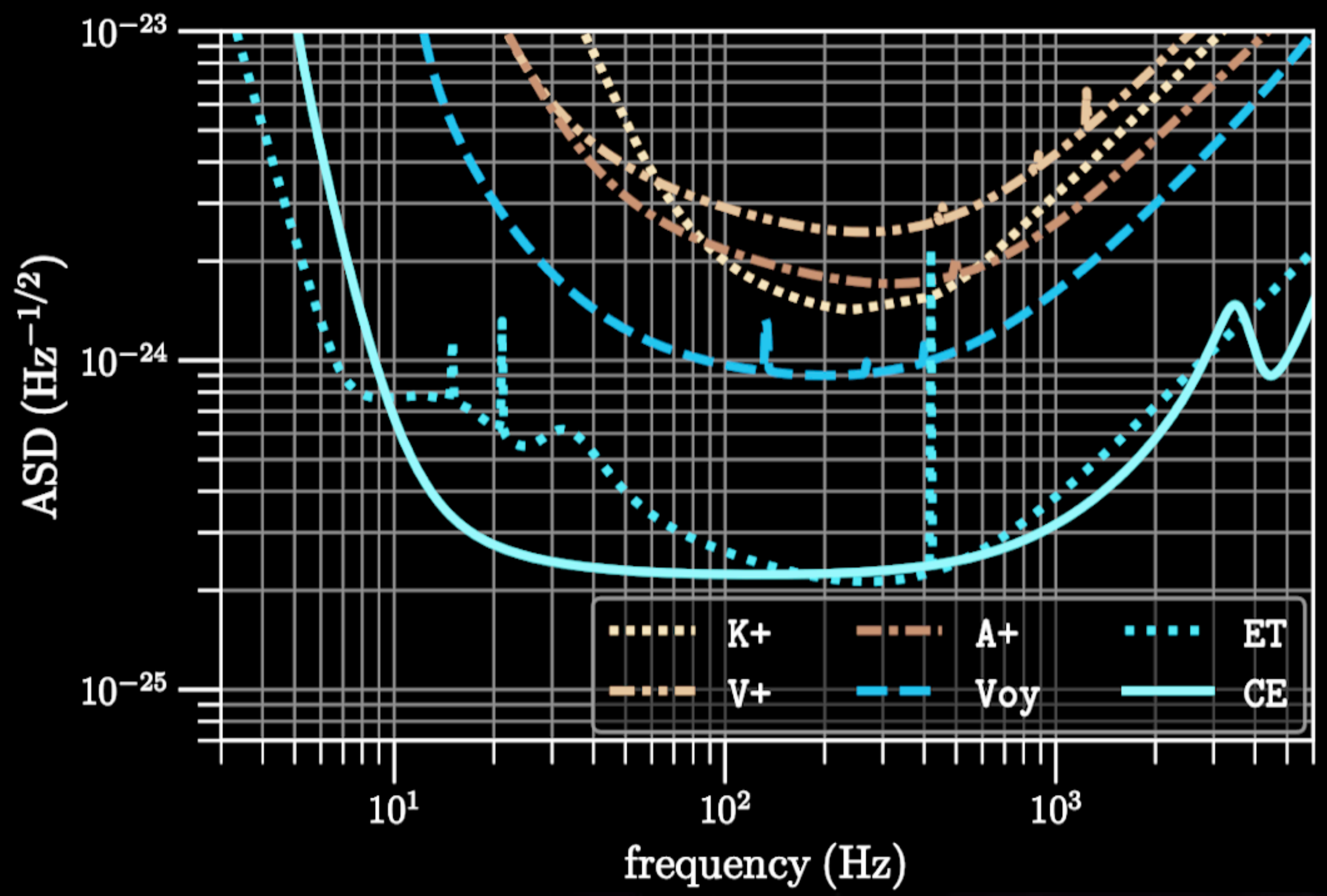
$\int_{t_d^{\min}}^{\text{collapse time}}$ $\int_{\text{collapse time}}^{t_d^{\max}}$

Merger rate density for BBH is a function of the collapse time. Higher collapse time implies more BNS and vice verse.



ASYMMETRIC DARK MATTER

BLACK HOLES FROM NEUTRON STAR IMPLOSION



Detectable ~~TOTAL~~ MERGER RATE

$$\dot{N} = \int_0^z \frac{\dot{n}(z')}{1+z'} \frac{dV_c}{dz'} dz' \, \epsilon(z') \rightarrow$$ Detector Efficiency

$$\epsilon(z' \,|\, \mathrm{SNR}_{\mathrm{thrsh}}, \sigma_{\tilde{\Lambda},\mathrm{thrsh}})$$

Detectability of source

Differentiability of source

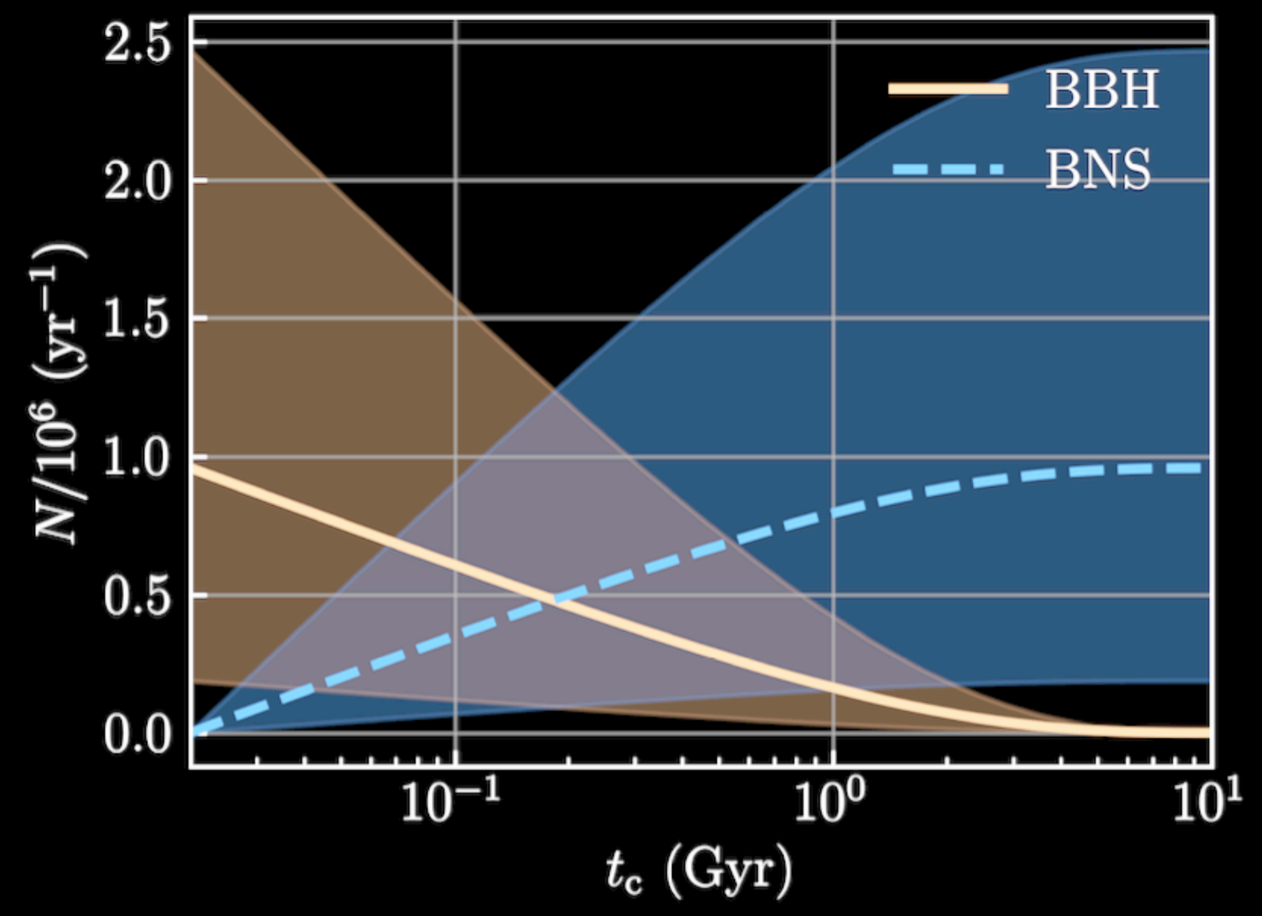
$\tilde{\Lambda}_{\mathrm{BBH}} = 0$

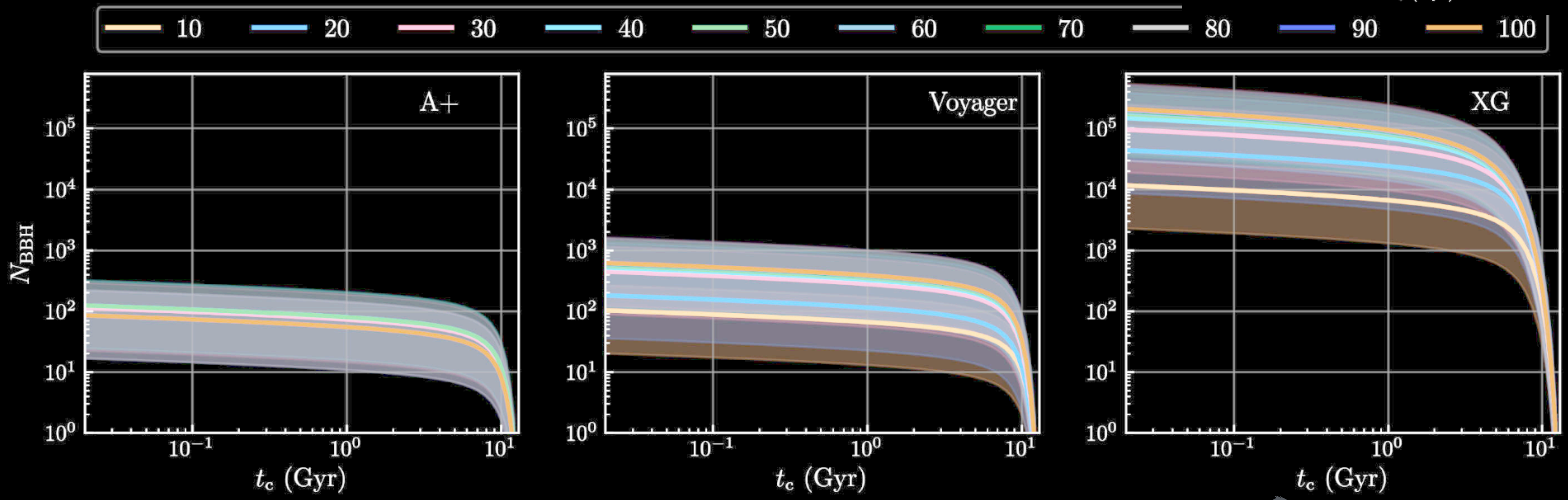
$\tilde{\Lambda}_{\mathrm{BNS}} > 0$

Image Credit: Karan Jani/Georgia Tech

ASYMMETRIC DARK MATTER

BLACK HOLES FROM NEUTRON STAR IMPLOSION



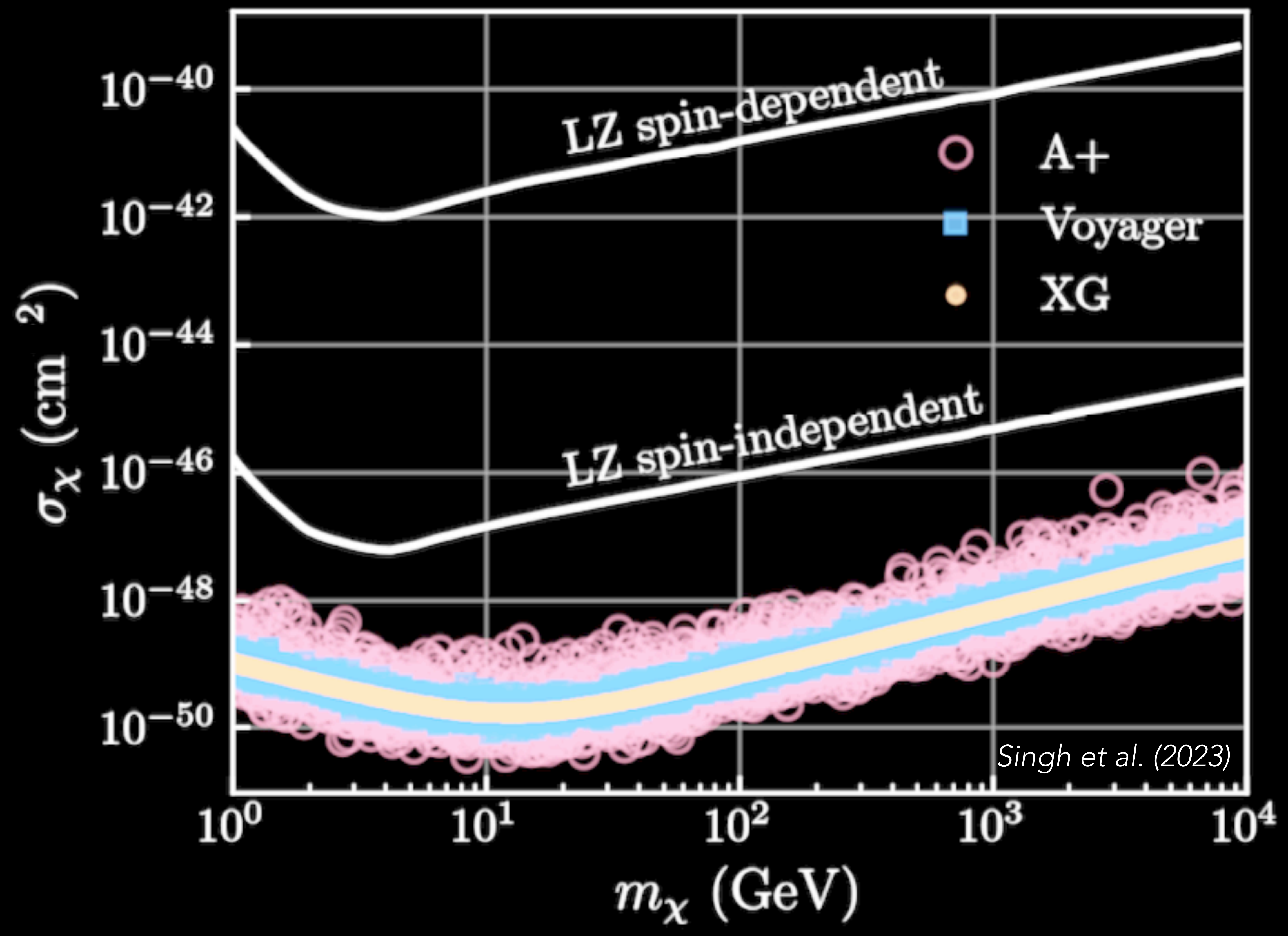


Increasingly Detectable and Differentiable

ASYMMETRIC DARK MATTER

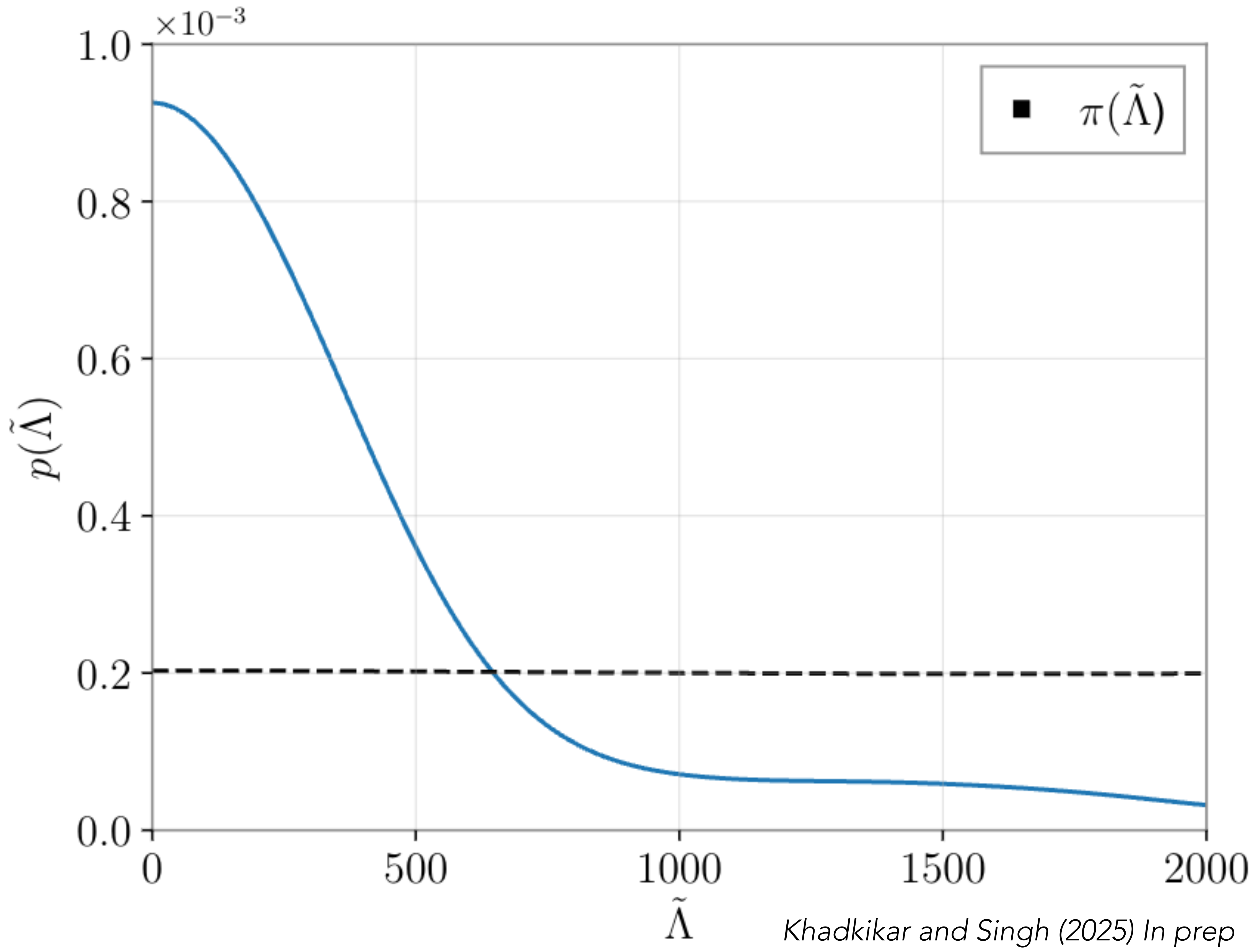
BLACK HOLES FROM NEUTRON STAR IMPLOSION

- Observed number of BBH is a function of collapse time.
- The collapse time depends on the scattering cross section and the mass of DM particle.
- Given some gravitational wave observations, we infer the collapse time and the particle properties of dark matter.



GW190425: BBH OR BNS?

Leveraging tidal information

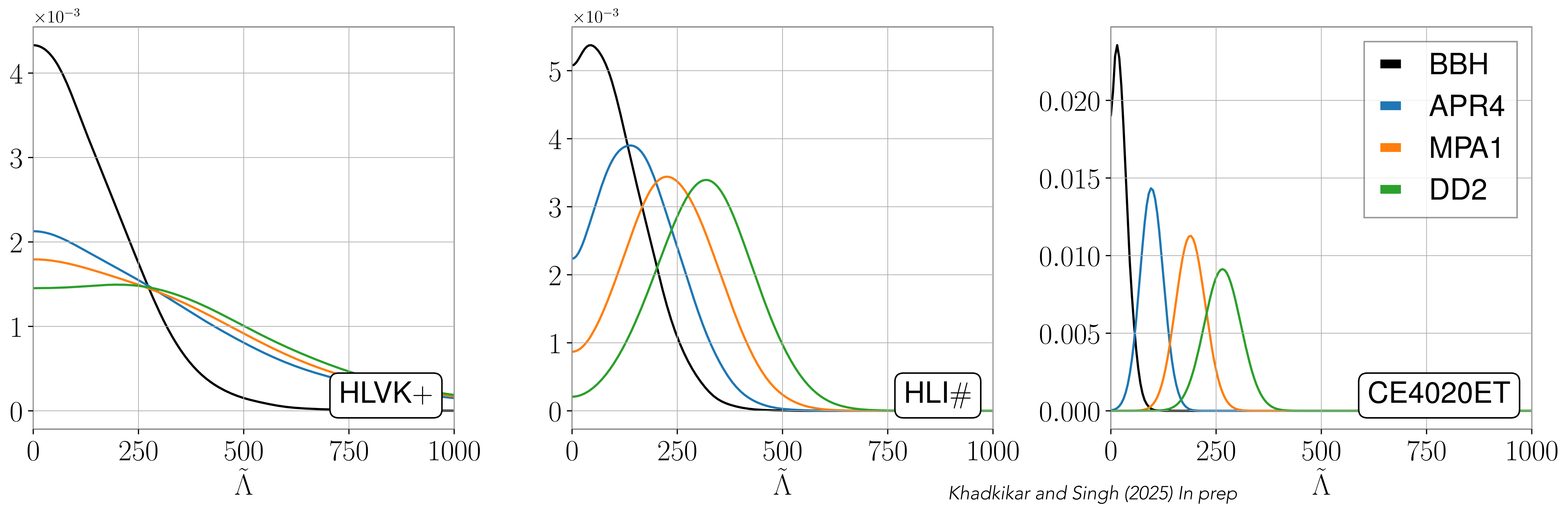


Khadkikar and Singh (2025) In prep

- The inferred effective tidal deformability, $\tilde{\Lambda}$ for GW190425
- $\tilde{\Lambda}$ = 0 is not excluded.

GW190425: BBH OR BNS?

Leveraging tidal information



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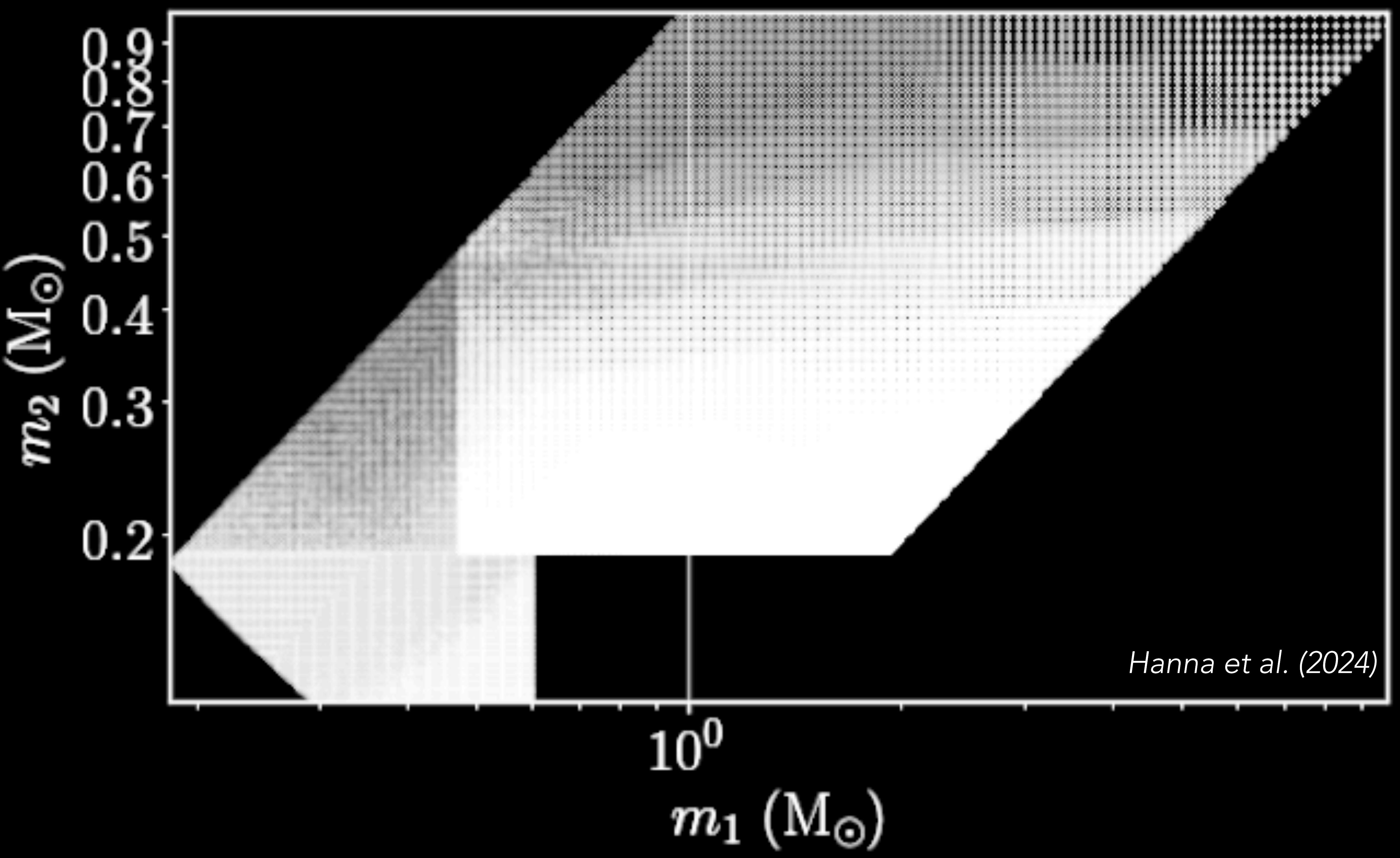
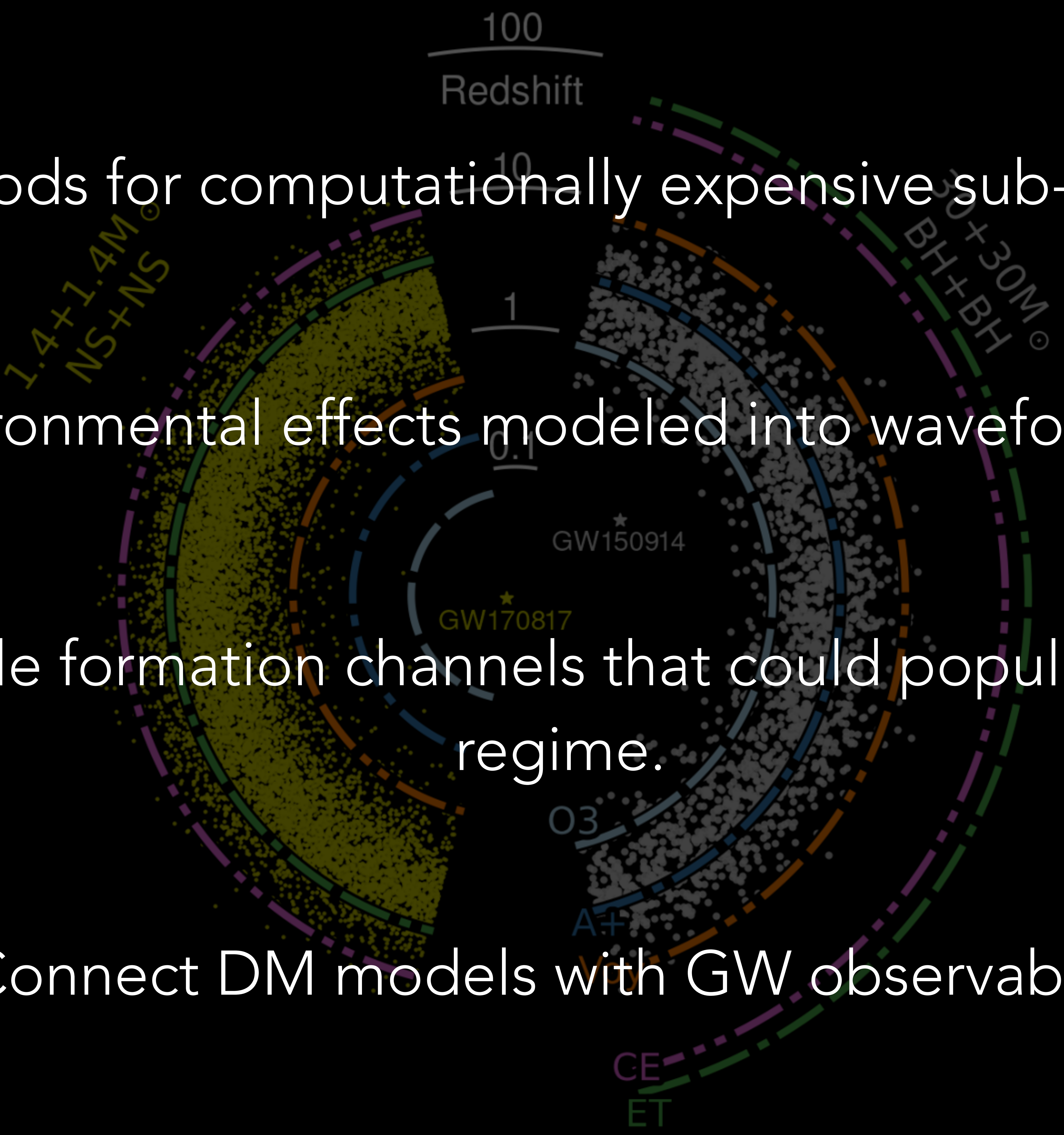


NEW METHODS FOR FUTURE DETECTORS

https://emfollow.docs.ligo.org/userguide/



New search methods for computationally expensive sub-solar mass searches

Environmental effects modeled into waveforms?

Methods to decouple formation channels that could populate the sub-solar mass regime.

Connect DM models with GW observables.

Bertone et al. (2019)

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